LLNL-PRES-557971

Physical Models for NIC
EOS, Opacity, Transport, Nuclear, Kinetics

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

Several physical models are important for manipulating HED matter to ignition

Laser Energy = 1.3 MJ

X-ray Energy = 1 MJ

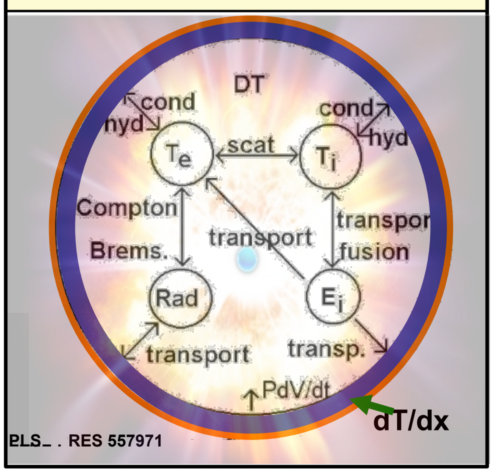
Energy to capsule =120 kJ
Set adiabat

Fuel K.E. = 12 KJ, Shell K.E. ~ 20 KJ

Hot spot = 10KJ

Burn propagation

Fuel assembly, transport,burn-physics



Several physical models are important for manipulating HED matter to ignition

Laser Energy = 1.3 MJ

Opacity, laser-plasma interaction, heat & e-transport

X-ray Energy = 1 MJ

Ablator opacity & EOS, drive Spectrum,radiation,e- production & transport

Energy to capsule =120 kJ
Set adiabat

Ablator opacity, drive spectrum, heat & radiation transport, CH & DT EOS

Fuel K.E. = 12 KJ, Shell K.E. ~ 20 KJ

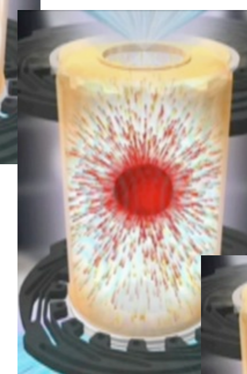
Heat transport, MIX, CH & DT EOS, Kinetics

Hot spot = 10KJ

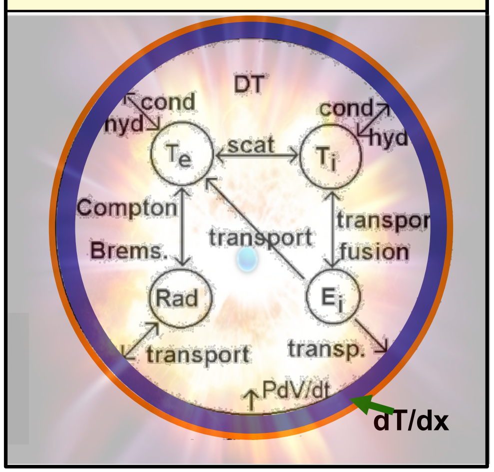
Transport, MIX, CH& DT EOS, Bremmstrahlung, reaction rates, Kinetics

Burn propagation






Fuel assembly, transport,burn-physics



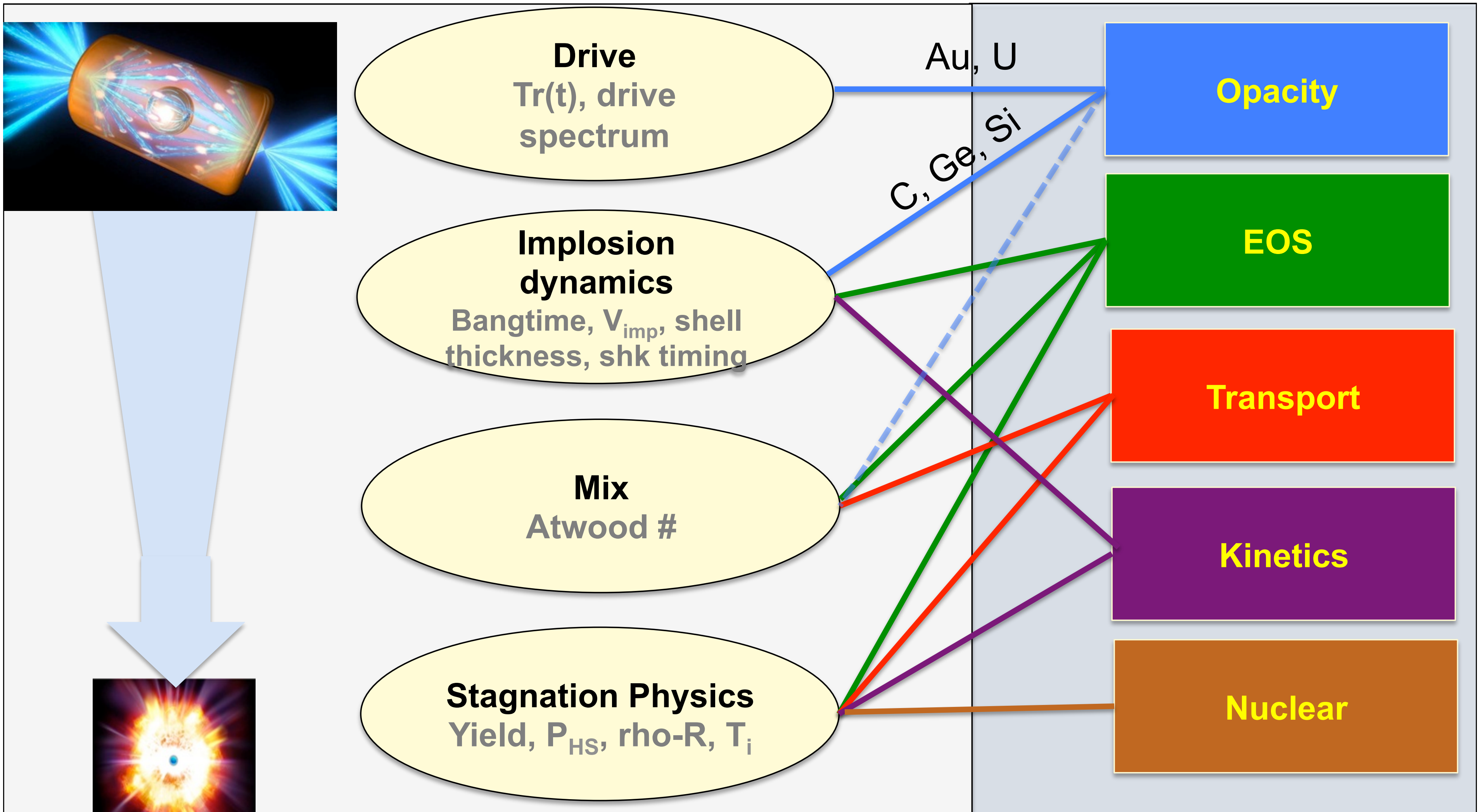
Several NIC discoveries are motivating improvements in our physical models

- **Drive and ablation physics:**
- Implosion velocity, V_{imp}, is low (EOS, Opacity, drive, Kinetics)
- V_{imp} difference between Si and Ge capsules (Opacity, drive)
- Ablator is thicker than predicted (EOS, NLTE, e- transport)
- Ablator release into D2 shows was initially off (EOS)
- Matching shock timing data with simulations requires drive multipliers (EOS, Opacity, drive, LPI)

- **Stagnation Physics and Mix:**
- Yield for a given V_{imp} and rho-R is low (EOS, Kinetics, transport)
- Hot spot pressure is low (EOS, Kinetics, transport)
- More low energy neutrons (<9MeV) than expected (Nuclear, kinetics)
- $\tau_{\text{Nuclear Burnwidth}} > \tau_{\text{x-ray burnwidth}}$ (transport)
- Mix cliff occurs at higher ablator mass than expected (Transport, kinetics)

Our panel will break up into groups focused on physical models, in contrast to implosion stages

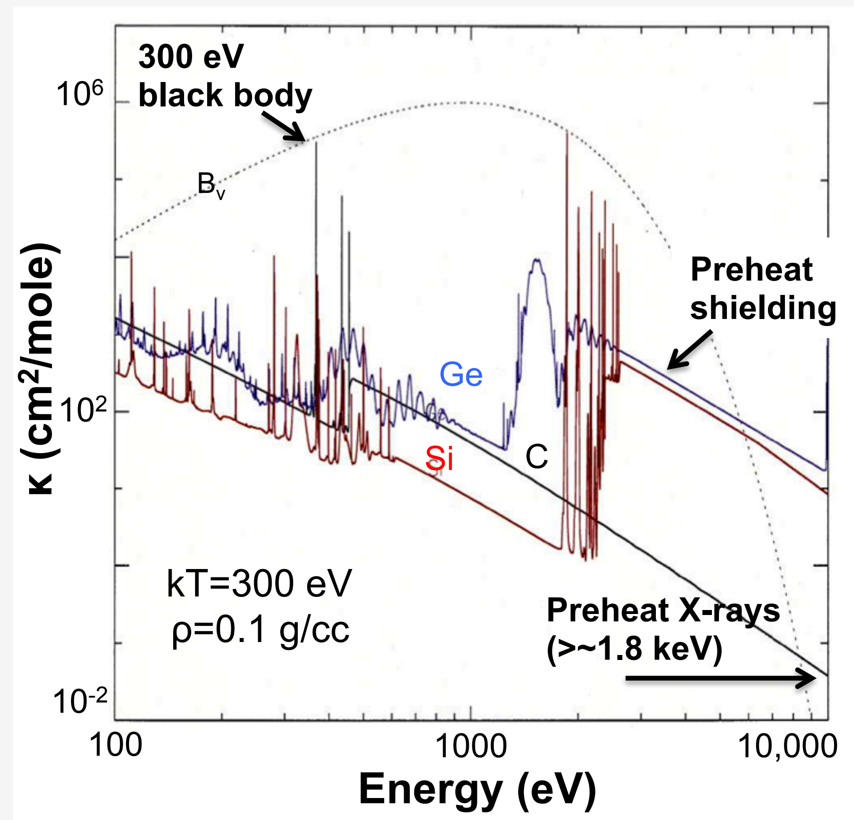
Implosion Performance and NIC Observables | **Physical models**



Optimizing implosion performance requires accurate opacities and emissivities (Si, C, Ge, Au, U)

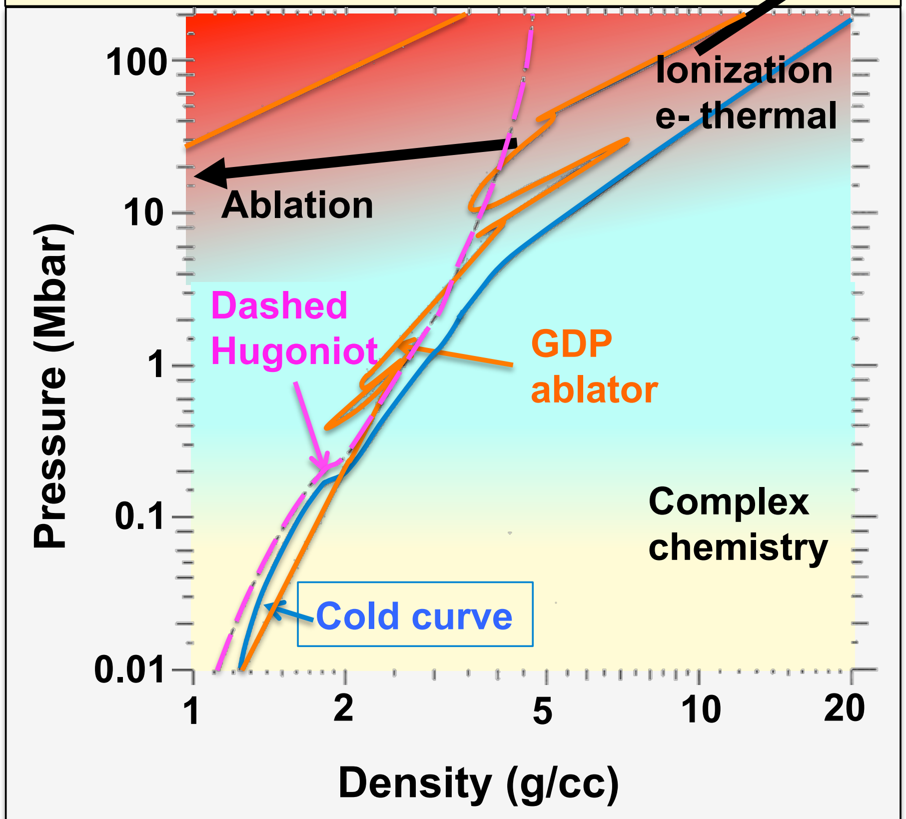
- **Ablator opacity (C, Si, Ge) is important for tuning ablation performance, mix and preheat.**
- **Both NLTE and LTE opacities have been improved recently (**H. Scott, S. Hansen, HEDP 6, (2010). B.G. Wilson, et al *PRE* **76**, 032103 (2007).) **but still DCA differs from more sophisticated models and EOS and Opacity are not self consistent.**
- **Important to consider convergence effects in photon binning and material zoning while considering effects of Opacity** (Hill and Rose)**.**

C, Ge and Si opacity at .1g/cc and 300 eV

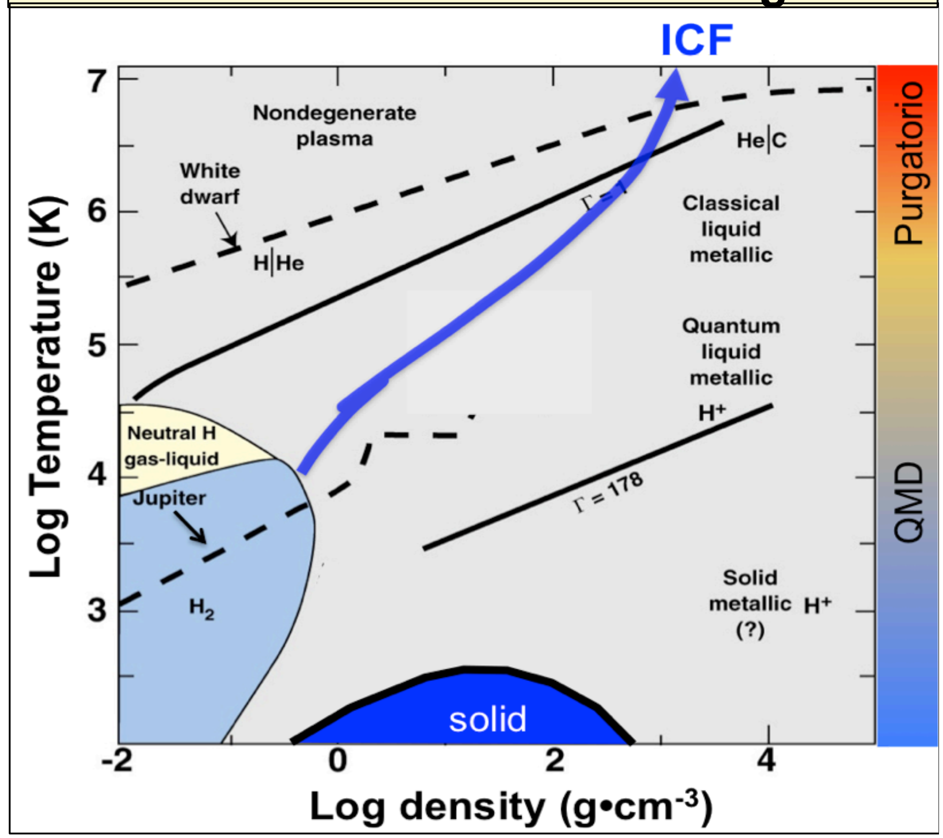


ICF requires knowledge of the hohlraum, ablator and fuel EOS over a broad range of conditions

Trajectory for glow discharge polymer (GDP), $CH_{1.3}$ ablator in ICF implosion



We need to know DT to 1.5 Kg/cc



Other ablator candidates include diamond, Be, B4C, Al

Transport processes implicit to forming a burning plasma are largely untested in relevant regeims

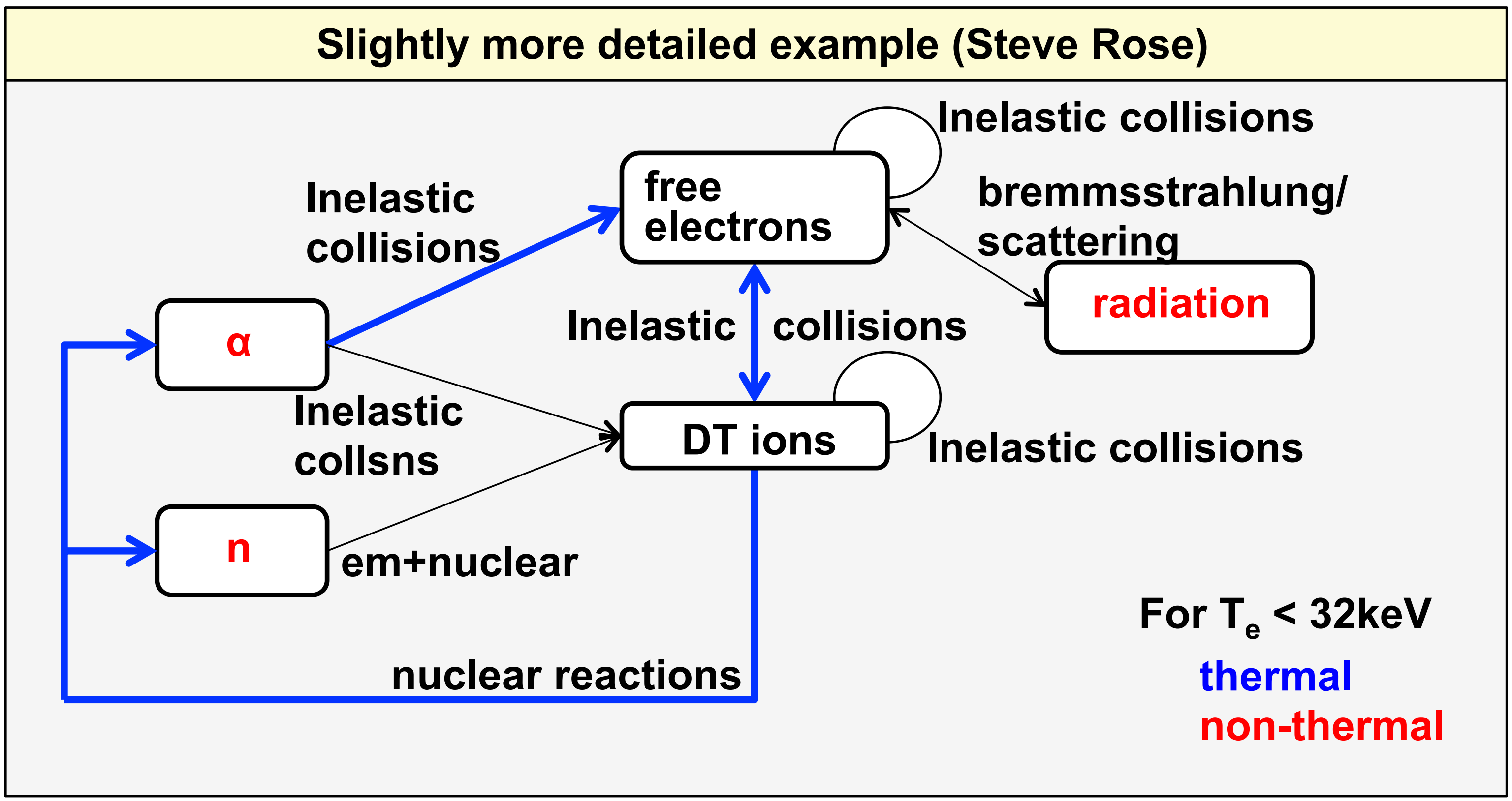
- e-ion coupling in hot spot & dense fuel:
- Stopping power in hot spot & dense fuel:
- Thermal conductivities hot spot & dense fuel:
- Thermal conductivities in CH

•Viscosity models…..

•How to handle mixtures…..

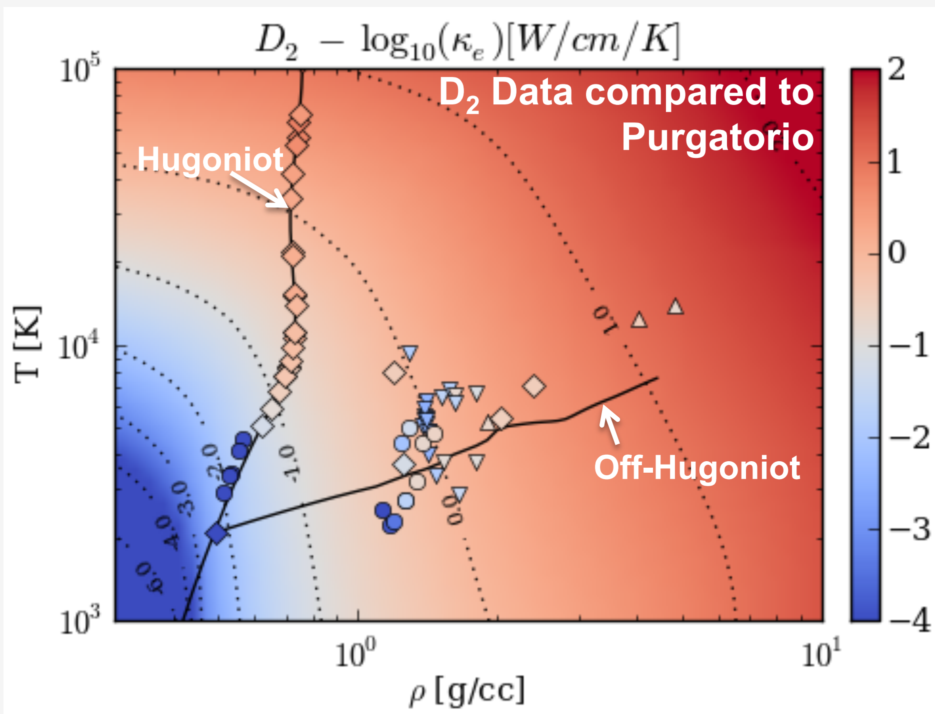
•Bremmstrahlung

•Compton scattering



Thermal conductivity is important for predicting mix and hotspot dynamics

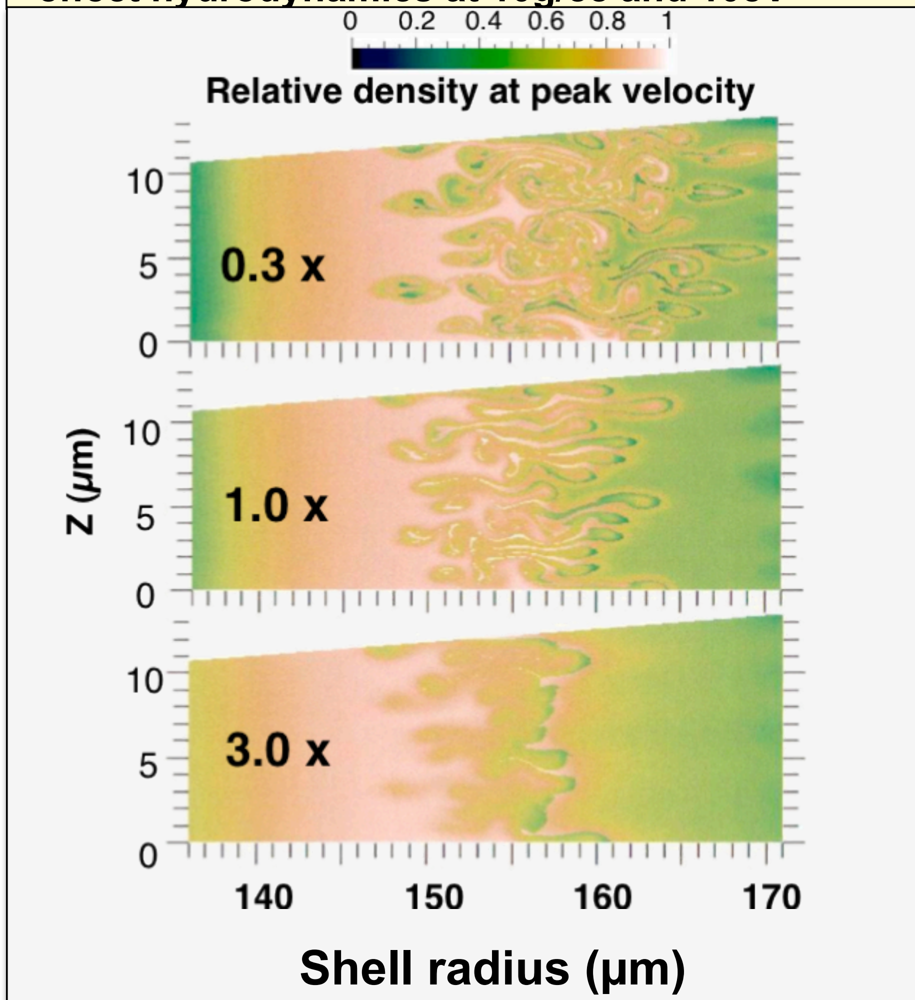
Purgatorio and QMD are in good agreement with D2 data on-Hugoniot but not off-Hugoniot



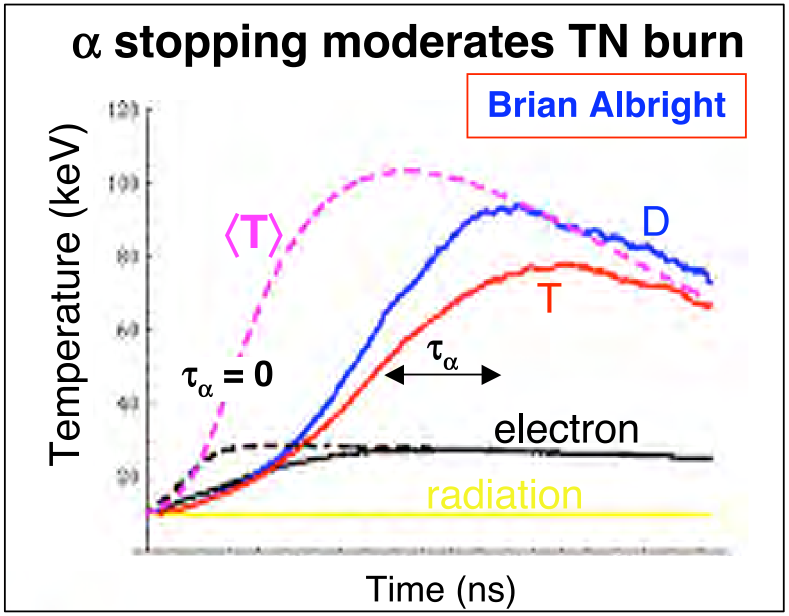
Experimental data: Nellis1992,○ Nellis1999, ○ Celliers2000,◇ Fortov2003,△ Ternovoi2009,▽ This work◇

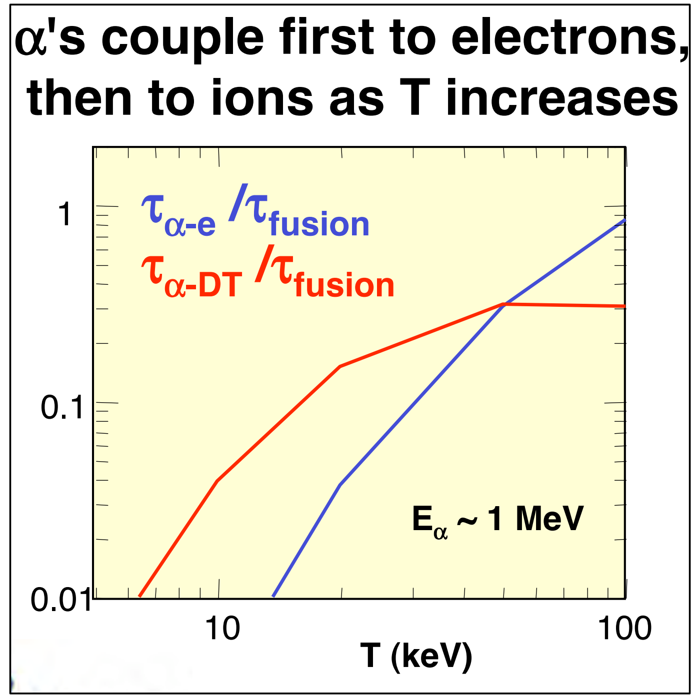
Theory: Purgatorio from Sterne et al.

Variations in thermal conductivity of a few times effect hydrodynamics at 10g/cc and 10eV



Thermonuclear burn in DT involves many complex processes of comparible time scales that compete with confinement time





G. Dimonte et al

Use VPIC code to simulate infinite D-T plasma @ ρ = 100 g/cc, T = 10 keV

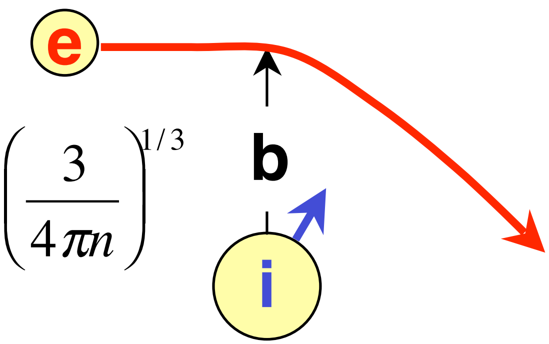
Bowers et al., Phys Plasma **15**, 55703 (08)

Kinetic ions, D, T, α's

Fluid electrons

Radiation energy sink

Electron ion equilibration is important for hotspot dynamics, shock equilibration, and laser coupling



$$a \equiv \left(\frac{3}{4\pi n} \right)^{1/3}$$

Particle collisions can be described by integrating Rutherford cross-section in Boltzman equation, but this diverges due to distant encounters

Plasma fluctuations due to discrete electrons & ions are described by Lenard-Balescu, but this diverges due to close encounters

$$\frac{dT_i}{dt} \sim \nu_{ie}\left(T_e - T_i\right)$$

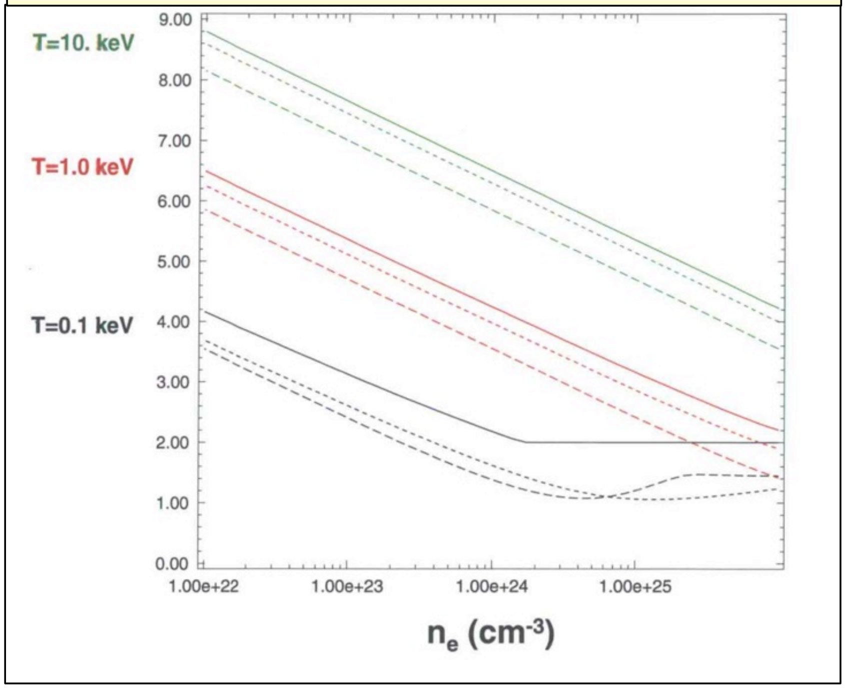
$$\nu_{process} \sim \nu_o \ln \Lambda_{process} \propto \frac{n}{T_e^{3/2}} \ln\left(\frac{b_{\max}}{b_{\min}}\right)$$ (relativistic correction)(degeneracy correction)

$$\Lambda_{ei}^2 = \frac{\lambda_D^2 + r_i^2}{b_{90}^2 + (\lambda_{dB}/2)^2}$$

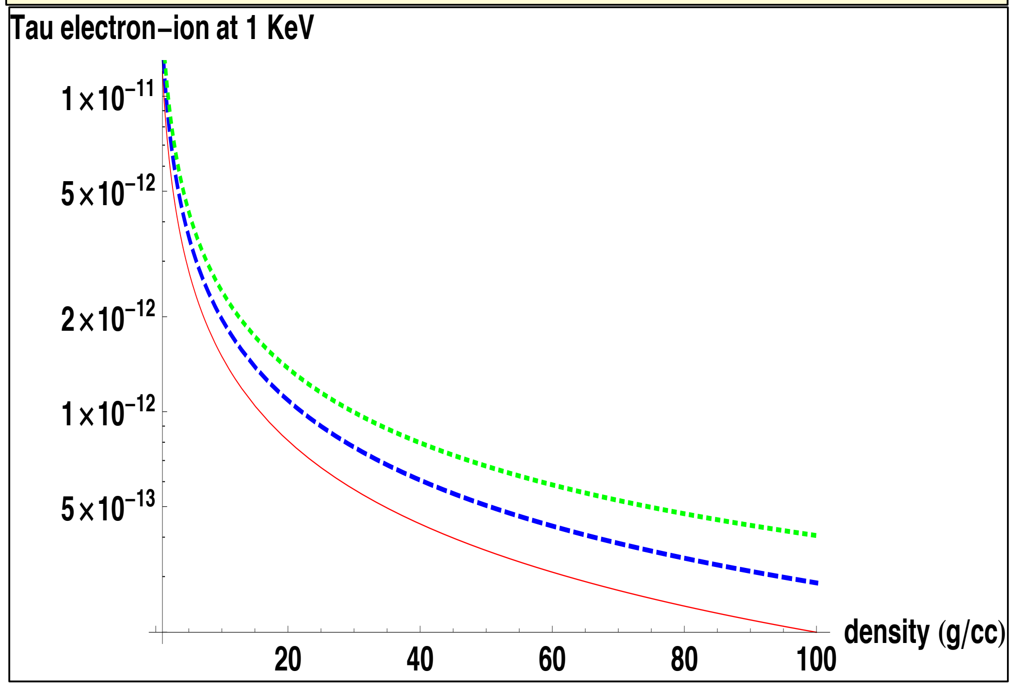
- **Lee & More, Phys Fluids, 27, 1273 (1984) includes simple models for degeneracy & limits on impact parameters**

Electron ion equilibration is important for hotspot dynamics, shock equilibration, and laser coupling

Log(Λ) for hydrogen Lee and More (solid), GMS (dotted), BPS(dashed)



Electron ion equilibration time for Lee and More (red), GMS(blue), and BPS (green)



Equilibration times are ~ps while burn durations 10-100 ps

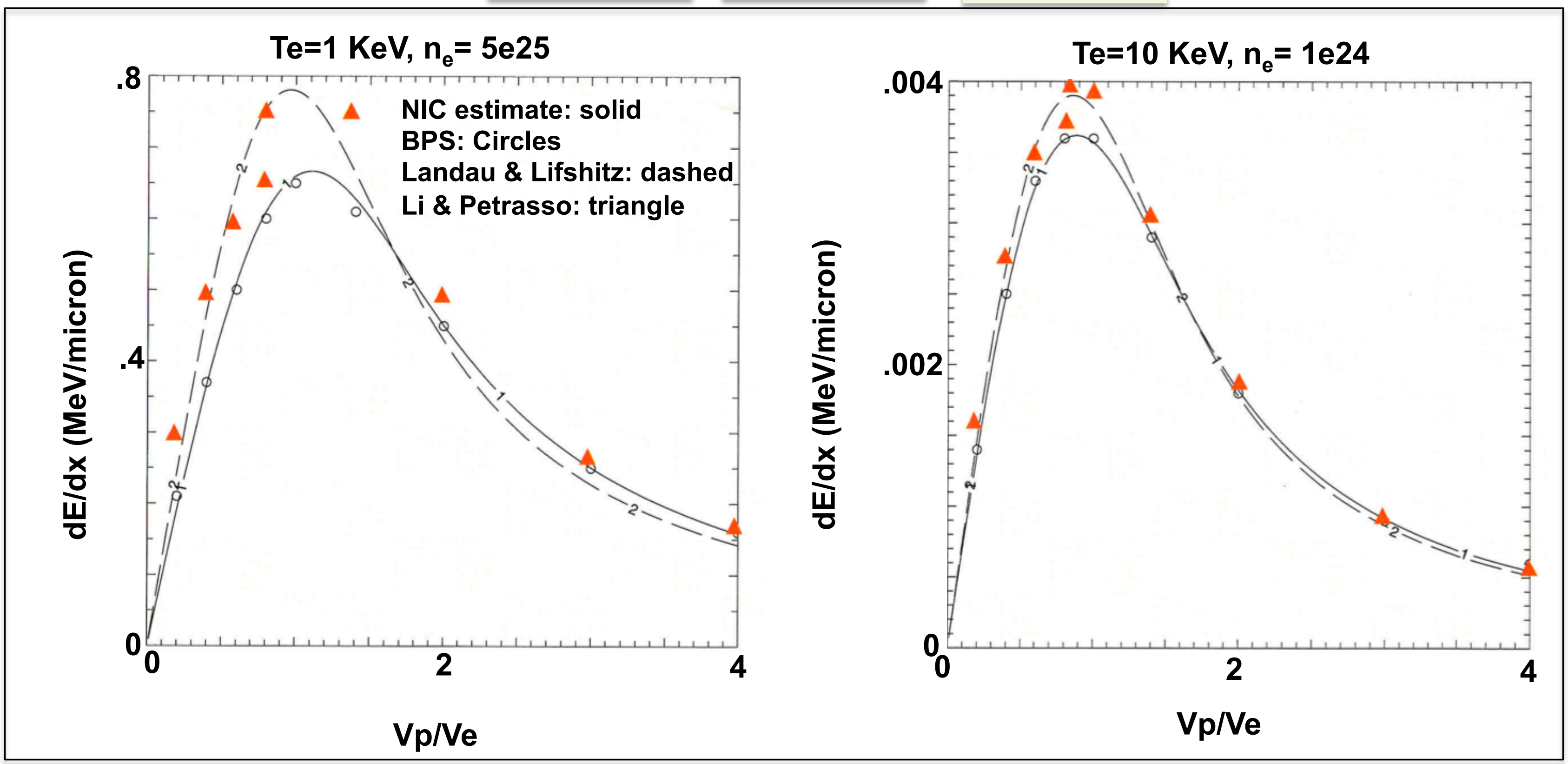
Details for stopping power

Stopping of charged particles is dominated by electron-ion interactions and contains ion-ion scattering

Alpha stopping | Contribution from Ions | Free e- | Bound e-

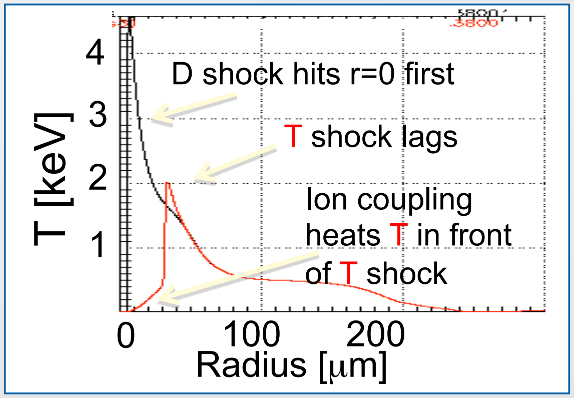
$$\frac{dE}{dx} = C_{ion}\left.\frac{dE}{dx}\right|_i + C_{ion}\left.\frac{dE}{dx}\right|_e + C_{ion}\left.\frac{dE}{dx}\right|_b$$

- Zimmerman, UCRL-JC-105616 (1990)
- Maynard & Deutsch, J. Physique, 46, 1113 (1985)



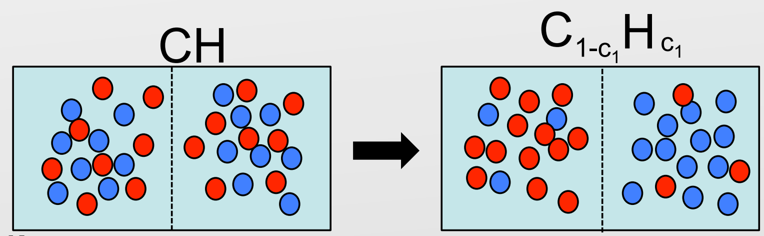
Summary of candidate multi-species and kinetic effects

Shock Separation



Pressure gradient-induced *E*-field causes lighter species to accelerate ahead of heavier species

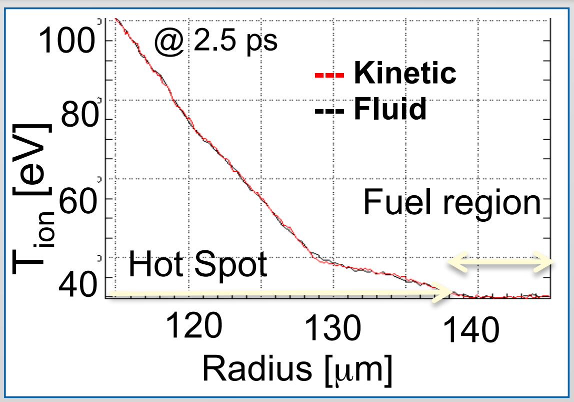
Species Separation in Ablator



$$\Phi_M = \frac{N_i}{2}\left[\Phi_H + \Phi_C + 7\Phi_e - k_B T\left(2\ln 9 + 7\ln(9/7)\right)\right] \qquad \Phi_U = \Phi_M + \Delta\Phi$$

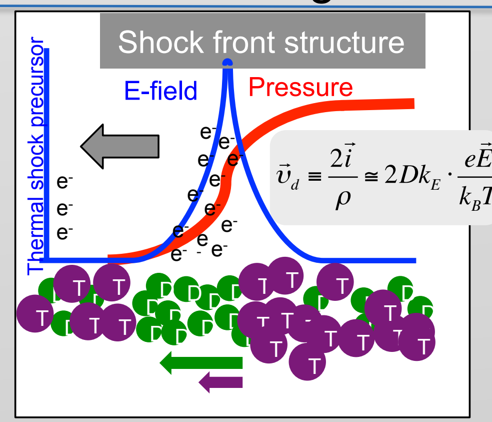
Some fraction of ablation energy goes into separating C from H, resulting in loss of ablation efficiency

Heating Due to Tail of Distribution



During hot spot formation, electrons in tail of energy distribution (~10 X Te) may heat fuel

Frictional Shock Heating of DT



Shocks in dense plasma cause relative drift speed between species: energy in directed V goes into heat

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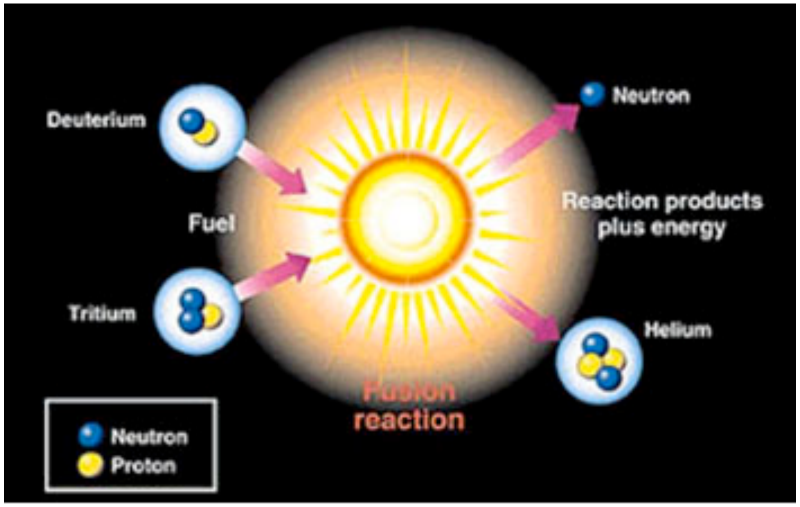
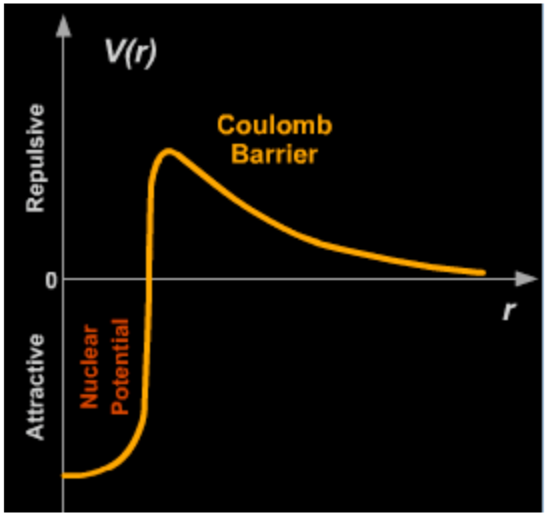
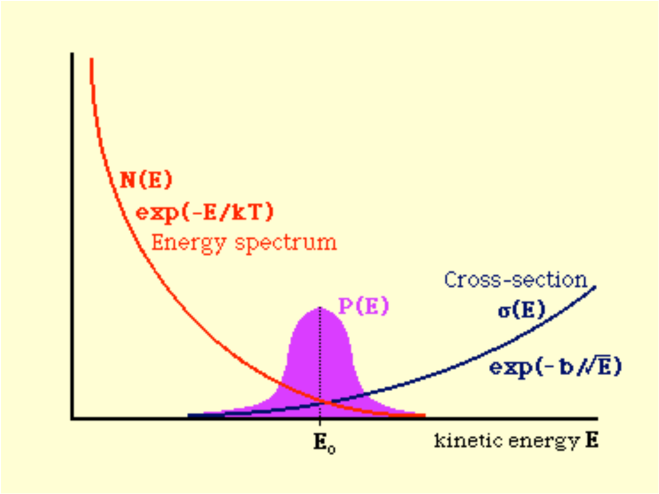
Thermonuclear Burn as well as nuclear diagnostic data interpretation depend on nuclear reaction rates







D-T reaction rate is extremely dependent on T_{ion}.

α-particles can heat up electrons and ions differently.

The first nuclear cross section measurement using an ICF facility has been made at Omega

PRL 107, 122502 (2011) PHYSICAL REVIEW LETTERS week ending 16 SEPTEMBER 2011

Measurements of the Differential Cross Sections for the Elastic n-^{3}H and n-^{2}H Scattering at 14.1 MeV by Using an Inertial Confinement Fusion Facility

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Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

D. P. McNabb, P. Navratil, and S. Quaglioni
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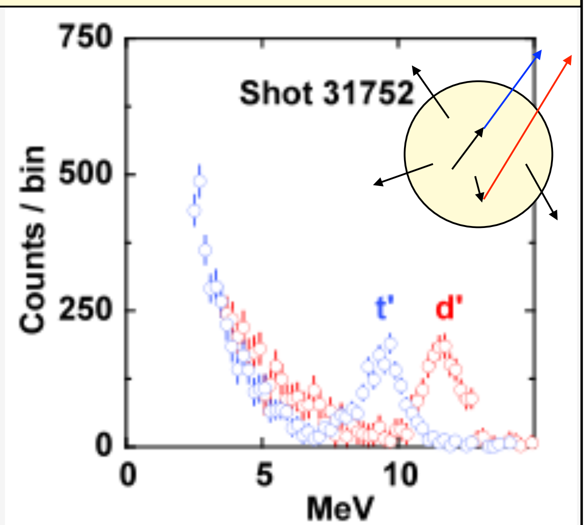
(Received 18 June 2011; published 15 September 2011)

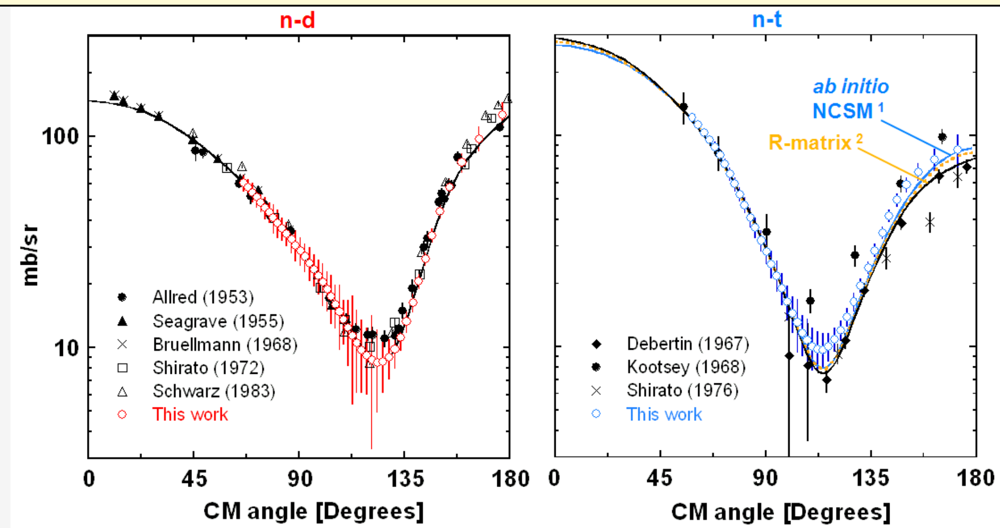
n-D,T Elastic Scattering

Plasma is neutron source and target



Simultaneous measurements of d' and t' spectra scattered by d-t neutrons.

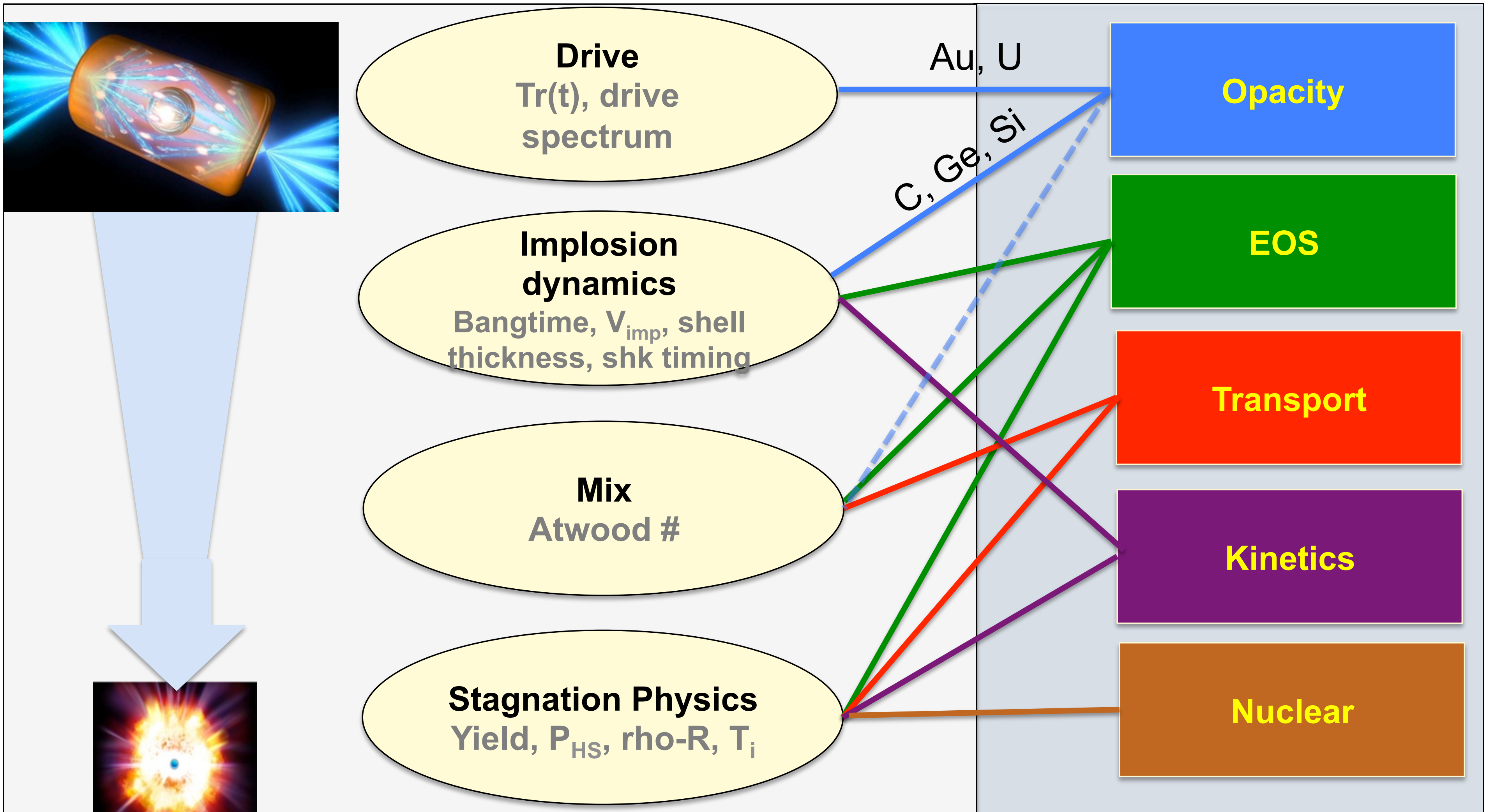
Comparison with ab initio calculations



1. P. Navrátil et al., LLNL-TR-423504 (2010).
2. Ga.A. Hale et al., Phys. Rev. C 42, 438 (1990).

Next several talks will outline each of the physics models in the codes. What are we missing?

Implosion Performance and NIC Observables **Physical models**



NIC

Details of our electron ion equilibration and stopping power follow in the next 6 vgs

Details for electron ion equilibration model used in NIC calculations

- Includes degeneracy, partial ionization, relativity, Lee & More ln(Λ)

$$\frac{de}{dt} = M_1 \cdot 8\alpha^2 \frac{m_e}{m_p} \frac{m_e c^2}{h} \frac{\text{"ln"}(\Lambda_{ei})}{(1+e^{-\mu/T_e})} \left(\sum_i n_i \frac{z_i^{*2}}{A_i} \right) k(T_i - T_e) \mathrm{R}(M_2 \frac{kT_e}{m_e c^2})$$

$$\mathrm{R}(\tau) = \frac{\mathrm{K}_{1/2}(1/\tau) + 2\tau \mathrm{K}_{3/2}(1/\tau)}{\mathrm{K}_2(1/\tau)}$$

$$\text{"ln"}(\Lambda) = \max\left[logmin, \frac{1}{2}\ln\left(1 + M_3 \Lambda^2\right) - C_1 + C_2 / \Lambda \right]$$

$$M_3 = M_3(reg) \frac{z^* + C_{3N}}{z^* + C_{3D}}$$

Many knobs to test sensitivities

NIC

Log Λ_{ei} is largely from Lee and More

- Lee & More, Phys Fluids, 27, 1273 (1984) includes simple models for degeneracy & limits on impact parameters

What is r_i for a mixture?

$$\Lambda_{ei}^2 = \frac{\lambda_D^2 + r_i^2}{b_{90}^2 + \left(\lambda_{dB}/2\right)^2}$$

When should ions be included?

$$\frac{4}{3}\pi r_i^3 = \frac{1}{n_i}$$

$$\frac{1}{\lambda_D^2} = 4\pi e^2\left(\frac{n_e}{kT_b} + \frac{\sum n_i z_i^{*2}}{kT_i}\right)$$

$$b_{90} = z^* e^2 / m_e v_b^2$$

$$\lambda_{dB} = \hbar / m_e v_e$$

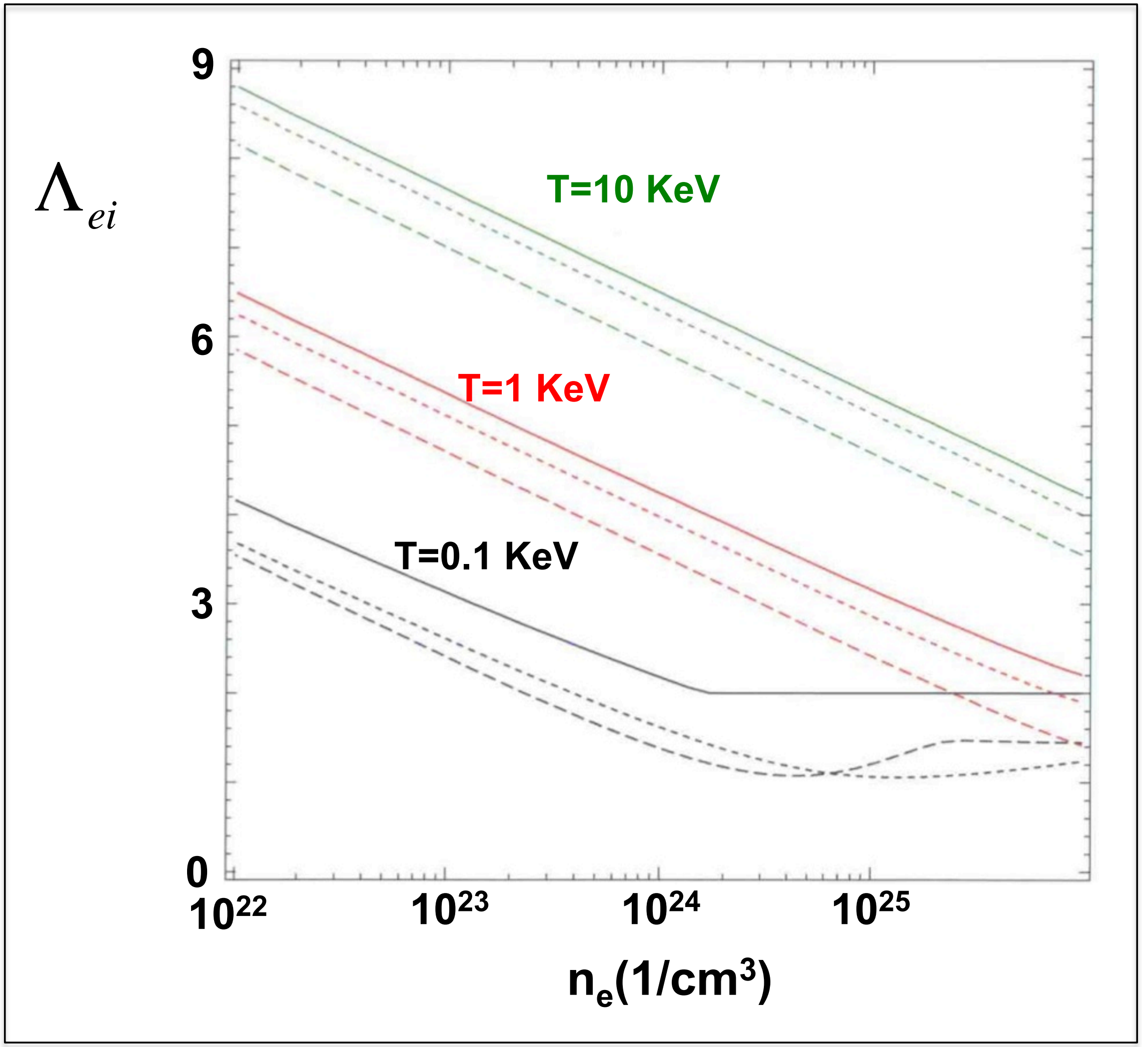
$$\frac{1}{2} m_e v_b^2 = \frac{3}{2} kT_b$$

$$T_b^2 = T_e^2 + \left(2/3E_F\right)^2$$

$$z^* = \sum n_i z_i^{*2} / n_e$$

Details for electron ion equilibration

Log(Λ_{ei}) for hydrogen: Lee & More (solid), GMS6 (dotted), BPS (dashed)



Details for stopping power

Stopping of charged particles is dominated by electron-ion interactions and contains ion-ion scattering

Alpha stopping | Contribution from Ions | Free e- | Bound e-

$$\frac{dE}{dx} = C_{ion}\left.\frac{dE}{dx}\right|_i + C_{ion}\left.\frac{dE}{dx}\right|_e + C_{ion}\left.\frac{dE}{dx}\right|_b$$

Ion contribution is small accept at very high Te or electron density

$$\left.\frac{dE}{dx}\right|_i = \frac{4\pi e^2 z_p^2}{v_p^2}\sum \frac{n_i z_i^{*2}}{m_i}\,\text{"ln"}(\lambda_D / b_i)$$

$$\lambda_D^2 = \frac{kT_e}{4\pi e^2 n_e} \qquad b_i^2 = \left(\frac{\hbar}{2m_r v_p}\right)^2 + \left(\frac{e^2 z_i z_p}{m_r v_p^2}\right)^2$$

Ions not included

- Zimmerman, UCRL-JC-105616 (1990)
- Maynard & Deutsch, J. Physique, 46, 1113 (1985)

Stopping of charged particles is dominated by electron-ion interactions and contains ion-ion scattering

Alpha stopping | Contribution from Ions | Free e- | Bound e-

$$\frac{dE}{dx} = C_{ion}\left.\frac{dE}{dx}\right|_i + C_{ion}\left.\frac{dE}{dx}\right|_e + C_{ion}\left.\frac{dE}{dx}\right|_b$$

Free electron stopping includes degeneracy and full range of ion-e$^-$ velocities

$$\left.\frac{dE}{dx}\right|_e = \frac{4\pi e^2 z_p^2}{m_e v_p^2} n_e L_e$$

$$L_e = \frac{1}{2}\,\text{"ln"}(\Lambda_e)\left(erf(y) - \frac{2}{\sqrt{\pi}} y e^{-y^2}\right)$$

$$\Lambda_e = \frac{2m_e v_e^2}{\hbar\omega_{pe}} \cdot \frac{0.321 + 0.259y^2 + 0.0707y^4 + 0.05y^6}{1 + 0.130y^2 + 0.05y^4}$$

$$y = v_p / v_e \qquad v_e = \sqrt{\pi}\,\frac{\hbar}{m_e}\left(4n_e\left(1 + e^{-\mu/T_e}\right)\right)^{1/3}$$

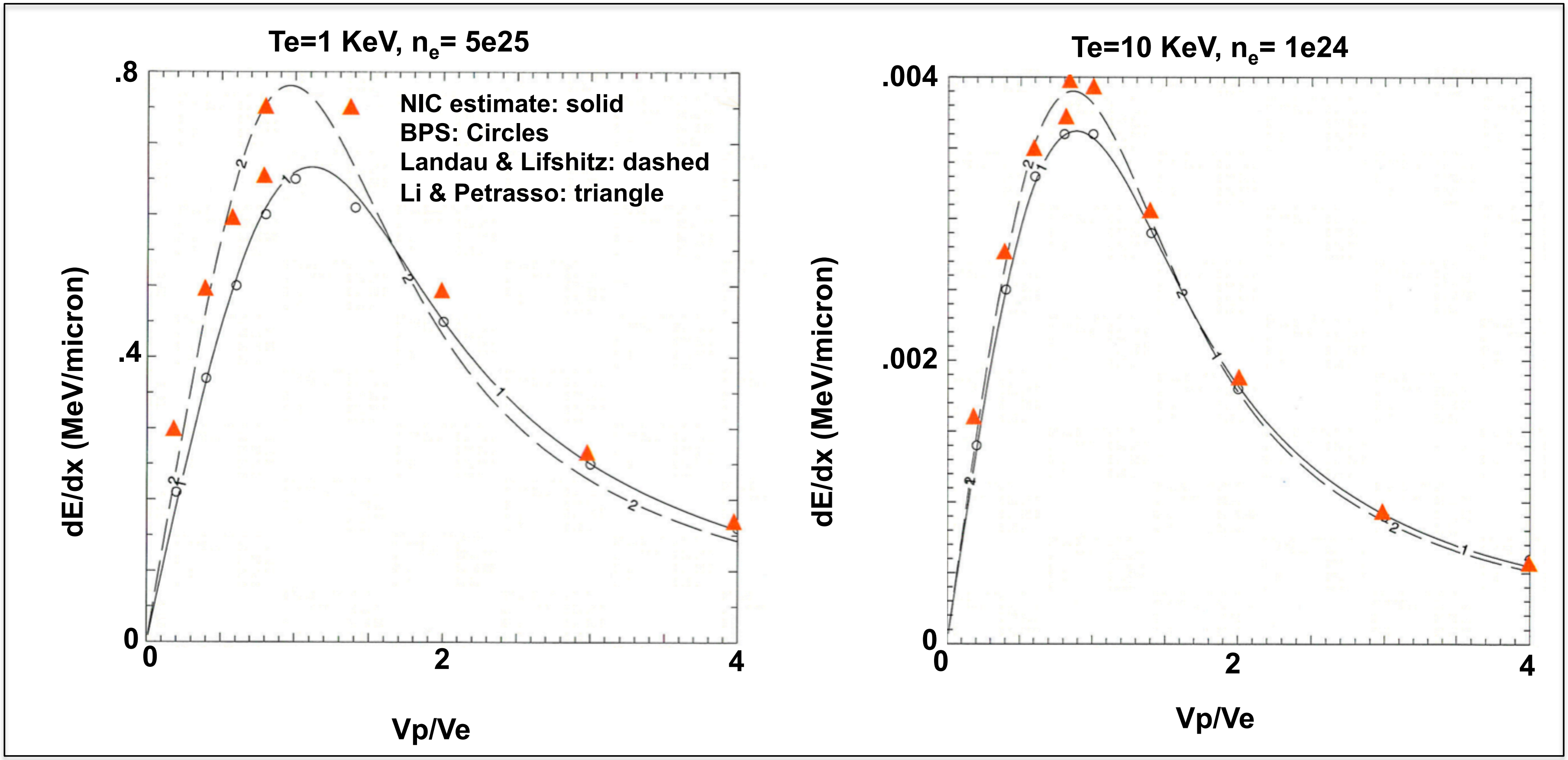
Bound electron stopping uses average excitation energy from More UCRL-84991, Sec VII

$$\left.\frac{dE}{dx}\right|_b = \frac{4\pi e^2 z_p^2}{m_e v_p^2} \sum n_i z_{ib} L_{ib} \qquad z_{ib} = z_i - z_i^*$$

$$L_{ib} = \frac{1}{2}\ln(1 + \Lambda_b^2) \qquad \Lambda_b = 2m_e v_p^2 / \bar{I}_i$$

$$\bar{I}_i = z_i \frac{0.024 - 0.013(z_{ib}/z_i)}{\sqrt{z_{ib}/z_i}} \quad \text{keV}$$

For burn conditions dE/dx used in ignition calculations agree with Brown, Preston and Singleton



End of Intro talk